J. of Fire Prot. Engr., 5 (3), 1993, pp 83–95

A METHOD FOR CALCULATION OF ELEVATOR EVACUATION TIME

John H. Klote
National Institute of Standards and Technology
Gaithersburg, MD 20899

SUMMARY

A detailed method of analysis of people movement by elevators during emergency building evacuation is presented. The time to evacuate a number of people using one group of elevators includes the sum of all the round trip times divided by the number of elevators plus the times needed to start up the elevator evacuation and to travel from the elevator lobby to the outside or to another safe location. A trip inefficiency is used to account for trips to empty floors and trips to pick up a few stragglers. The method includes detailed analysis of elevator car travel including constant acceleration, transitional acceleration, constant velocity, transitional deceleration, constant deceleration, and leveling. The time for people to enter and exit the elevator car is addressed including inefficiencies for elevator door sizes and types. The impact of elevator arrangements is addressed, and the difference between commonly accepted and unusual arrangements is presented. A computer program, ELVAC, was written to calculate elevator evacuation time, and an example calculation of evacuation time is provided using this program.

INTRODUCTION

Throughout most of the world, signs next to elevators indicate they should not be used in fire situations; stairwells should be used for fire evacuation. These elevators are not intended as means of fire egress, and they should not be used for fire evacuation[1]. The idea of using elevators to speed up fire evacuation and to evacuate persons with disabilities has gained considerable attention[2-8].

This paper was part of a project sponsored by the U.S. General Services Administration (GSA) to study occupant use of elevators during building evacuations. Aspects of emergency elevator evacuation addressed in this project were systems concepts, engineering design considerations, human behavior, and elevator smoke control[9]. A discussion of this research, related research, industry concerns, and recent ideas about elevator evacuation is provided by Klote et al[10]. For information specifically about human considerations concerning elevator evacuation, the reader is referred to Groner and Levin[11].

This paper presents a detailed method for calculation of people movement time needed for evacuation by elevators during an emergency, based on principles of elevator engineering[12]. Bazjanac[3] and Pauls[4] have developed methods of calculation of evacuation time by elevator, but the method presented here incorporates more detail about elevator motion and elevator loading and unloading. A computer program, ELVAC, for calculation of elevator evacuation time is described including an example. ELVAC calculates the evacuation time for one group of elevators, but ELVAC can be used a number of times to calculate the elevator evacuation times for a building with more than one group of elevators. For a listing of the program and example calculations see Klote and Alvord[12].

The sequence of elevator operation for emergency evacuation is complicated and has many possible variations. The following general sequence is presented to provide a framework for the method of analysis presented in this paper. Upon activation of emergency evacuation, elevators in normal service will go to a discharge floor where any passengers on the elevators will exit. This discharge floor may either lead to the outside or lead to an area of relative safety where people may stay during the fire. The elevators will make a number of round trips to transfer occupants from other floors to the discharge floor. During evacuation, the elevators may be under a special emergency evacuation mode of automatic control or under manual control.

The evacuation time addressed in this paper is an idealized time for people movement which does not account for the complex human behavior that often occurs during emergencies. It is believed that the analysis of this paper is about as accurate as that for evacuation by stairs*. There is little guidance available regarding the extent to which actual evacuation time is greater than the idealized times for stairs or elevators, but Nelson and MacLennan[13] indicate that actual evacuation time can be two or even three times as long. The approximate nature of such calculations should be taken into account in any applications of the methods presented in this paper.

EVACUATION TIME

Analysis of people movement during elevator evacuation must take into account the number and arrangement of elevators in a building. Generally elevators are located in groups of up to eight elevators. Elevators in a group are located near each other and are controlled together to efficiently move people. Arrangements of elevator groups are discussed later. The method of analysis and the computer program of this paper are for the calculation of the evacuation time for one group of elevators. For buildings with multiple groups of elevators, the approach presented in this paper can be applied separately to each group of elevators.

Ideally the time to evacuate a number of people using one group of elevators consists of the sum of all the round trip times divided by the number of elevators plus the time needed to start up the elevator evacuation and the travel time from the elevator lobby to the outside (or to another safe location). Accounting for inefficiencies of elevator operation, this evacuation time can be expressed as

$$t_e = t_a + t_o + \frac{(1+\eta)}{J}\sum_{j=1}^{m} t_{r,j} \tag{1}$$

where $t_{r,j}$ is the time for round trip j, m is the number of round trips, J is the number of elevators, η is the trip inefficiency, t_a is elevator evacuation start up time, and t_o is the travel time from the elevator lobby to the outside or to another safe location. The round trip time depends on the travel time of the elevator and on the number of people carried by the elevator as discussed later. The travel time from the elevator lobby to a safe location can be evaluated by conventional methods of people movement [i.e. Nelson and MacLennan[13] or Pauls[14]]. The trip inefficiency accounts for trips to empty floors and trips to pick only a few stragglers. The elevator evacuation start up time is discussed in the next section.

The number of elevators, J, used in Equation 1 may be less than the number of elevators in the group to account for out-of-service elevators. The probability of elevators being out-of-service depends on a number of factors including the age of the elevators and the quality of maintenance. Because the out-of-service condition can significantly increase elevator evacuation time, any analysis of elevator evacuation should take this condition into account.

* For a discussion of times for people movement during emergency evacuation on stairs, readers are referred to Nelson and MacLennan[13] and Pauls[14].

Start Up Time

The elevator evacuation start up time is the time from activation to the start of the round trips that evacuate people. For automatic elevator operation during evacuation, a simple approach is to start elevator evacuation after all of the elevators have been moved to the discharge floor. For this approach, the start up time, t_a, consists of the time for elevators to go to the discharge floor plus the time for the passengers to leave the elevators. This can be expressed as

$$t_a = t_T + (t_u + t_d)(1+\mu) \qquad (2)$$

where t_T is the travel time for the elevator car to go from the farthest floor to the discharge floor, t_u is the time for passengers to leave the elevator, t_d is the time for the doors to open and close once, and μ is the total transfer inefficiency. These terms are discussed in detail later.

An alternative to the simple approach discussed above consists of starting the evacuation operation individually for each elevator when it reaches the discharge floor. This alternative could result in slightly reduced evacuation time. However, this alternative is not discussed further here, because of its limited benefit and added complexity.

For manual elevator operation, the time for elevator operators to be alerted and then get to the elevators must be included in the estimate of start up time. This additional time may be considerably greater than that calculated from Equation 2.

Elevator Round Trip Time

The round trip starts at the discharge floor and consists of the following sequence: elevator doors close, car travels to another floor, elevator doors open, passengers enter the car, doors close, car travels to discharge floor, doors open, and passengers leave the car. The round trip time, t_r, is can be written as

$$t_r = 2t_T + t_s \qquad (3)$$

where t_s is the standing time and t_T is the travel time for one way of the round trip. This equation is based on the elevator only stopping at one floor to pick up passengers. It is expected that most elevators will fill up on one floor and proceed to the discharge floor. What constitutes a full elevator is discussed later. If an elevator stops to pick up passengers at more than one floor during a round trip, Equation 3 can be modified accordingly. However, the trip inefficiency accounts for such multiple stops.

Standing Time

The standing time is the sum of the time to open and close the elevator doors twice, the time for people to enter the elevator, and the time for people to leave the elevator. Considering transfer inefficiencies, the standing time for a round trip can be expressed as

$$t_s = (t_i + t_u + 2t_d)(1+\mu) \qquad (4)$$

where

$$\mu = \alpha + \varepsilon + \gamma$$

The basic transfer inefficiency, α, allows for rounding off of probable stops, door operating time, door starting and stopping time, and the unpredictability of people. Typically a value of 0.10 is used for the basic transfer inefficiency for commonly accepted arrangements of elevator groups as illustrated in Figure 1. For each of these arrangements, the configuration of the elevator lobby is such that passengers can recognize which elevator has arrived and get on the elevator without excessive delay. Further, these lobbies have sufficient space so that people exiting one elevator will have a minimal impact on the flow of people leaving another elevator.

Arrangements of elevator groups other than those commonly accepted can be less efficient and require an increased value of the basic transfer inefficiency. These unusual arrangements include cars separated

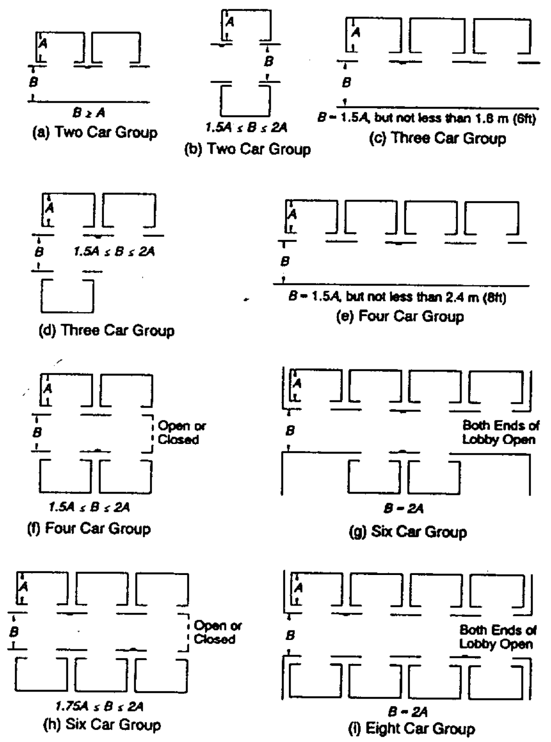


Figure 1. Commonly accepted elevator arrangements

(Figure 2a, too many cars in a line Figure 2b, angular arrangement Figure 2c, and cornered arrangement Figure 2d.) Separation of elevators results in increased boarding time for passengers waiting by one elevator to walk to another when it arrives. If the separation is too large, some passengers choose to let elevators go by without boarding. Use of too many elevators in a line has similar inefficiencies. With the angular arrangement Figure 2c, cars at the narrow end tend to be to close together while cars at the wide end tend to be too far apart. In the cornered arrangement Figure 2d, passengers entering or leaving corner cars tend to interfere with each other.

The door inefficiency, ε, is used to adjust for any increase in transfer time over that of a 1200 mm (48 in) wide center opening door. Values of ε are listed in Table 1. The inefficiency, γ, is used to account for any other inefficiencies in people transfer into or out of elevators, such as increased movement times within an elevator car due to an unusual elevator car shape or limited physical capability of passengers. For example, γ often is chosen to be 0.05 for hospital elevators. Generally for office buildings, γ is taken as zero.

The time, t_d, for the doors to open and close depends on the width and type of the doors as listed in Table 1. The kinetic energy of closing doors is limited by elevator safety

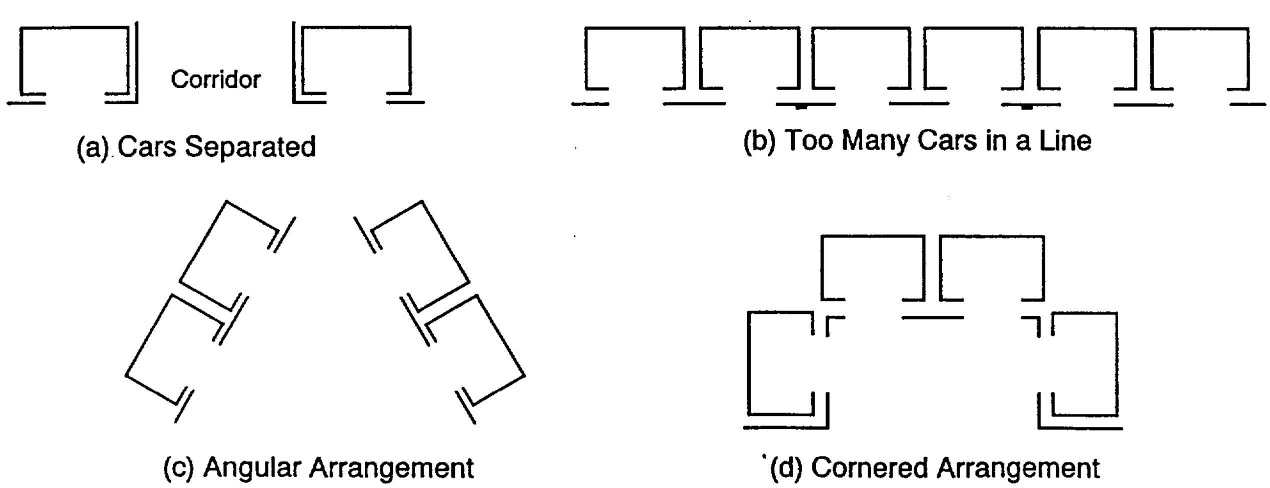


Figure 2. Unusual elevator arrangements resulting in inefficient people movement

Table 1
Door Operating Time and Transfer Inefficiency

Door Type	Width mm (in)	Time[1] to Open & CloseDoor t_d (s)	Transfer Inefficiency ε
A. Single-Slide	900 (36)	6.6	0.10
B. Two-Speed	900 (36)	5.9	0.10
C. Center-Opening[2]	900 (36)	4.1	0.08
D. Single-Slide	1100 (42)	7.0	0.07
E. Two-Speed	1100 (42)	6.6	0.07
F. Center-Opening[2]	1100 (42)	4.6	0.05
G. Two-Speed	1200 (48)	7.7	0.02
H. Center-Opening[2]	1200 (48)	5.3	0
I. Two-Speed	1400 (54)	8.8	0.02
J. Center-Opening[2]	1400 (54)	6.0	0
K. Two-Speed	1600 (60)	9.9	0.02
L. Center-Opening[2]	1600 (60)	6.5	0
M. Two-Speed, Center-Opening[2]	1600 (60)	6.0	0

[1]Time to open and close doors includes 0.5 second for car to start.
[2]When pre-opening can be used, the time to open and close these doors can be reduced by 1 second.

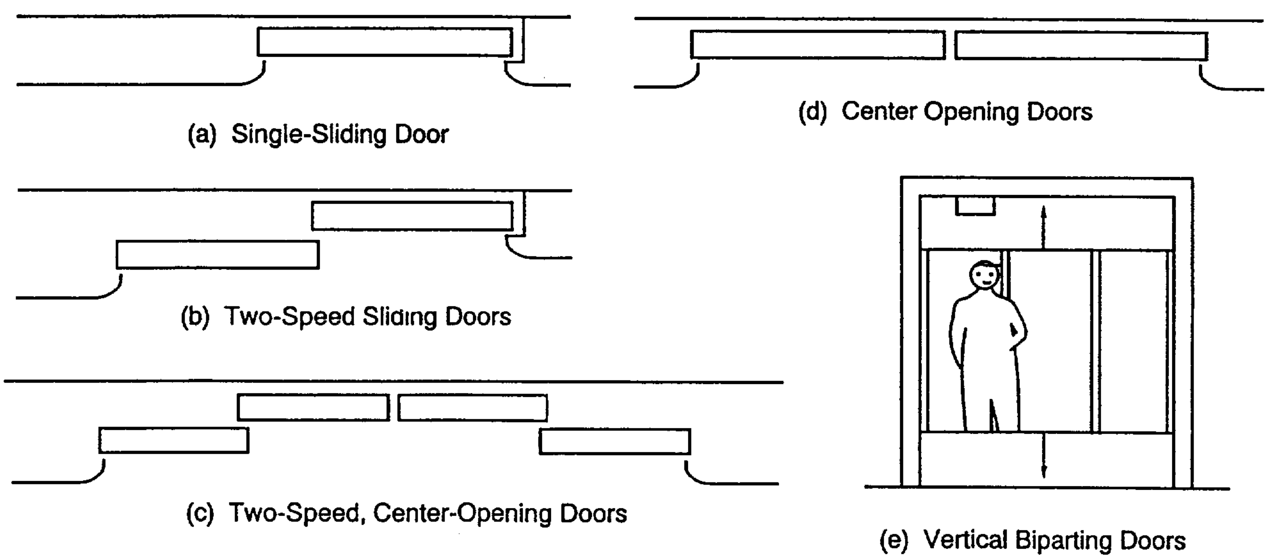


Figure 3. Types of elevator doors

codes and is usually not more than 0.29 J (7 ft poundal‡). This is why doors from different manufacturers take about the same time to open and close. Types of elevator doors are shown in Figure 3. Door operating time is important because of the many times that doors open and close during an evacuation. Further, an elevator can not leave a floor before the doors are closed and locked, and passengers can not leave an elevator until the doors are fully opened or nearly fully opened. Generally elevator doors do not open until the car has stopped and is level with the floor. However, some center

‡The poundal is the unit of force in the pound mass-poundal system of units, and one poundal equals a force of about 0.138 newtons (0.0311 pounds).

opening doors start opening while the car is leveling, and the times listed in Table 1 should be reduced by one second for these preopening doors.

The time, t_i, for people to enter an elevator depends on the number, N, of people entering and on the door operation. As previously stated, it is expected that most elevators will fill up on one floor and proceed to the discharge floor. However, elevators will be less than full when there are not enough people waiting in the lobby to fill an elevator or elevators. Thus the analysis must include partially filled elevators. Strakosch[16] has observed elevator loadings for which passengers will not board an elevator and choose to wait for the next one. These observed values are based on 0.22 m^2 (2.3 ft^2) of floor space in the elevator car per person. It should be noted that the ASME A17.1[15] elevator standard allows a maximum loading at 0.14 m^2 (1.5 ft^2) per person, but this high density is not achieved in normal practice. For this study, the observed values of Strakosch are used as the number of persons in a full elevator car, and these loadings are listed in Tables 2 and 3.

Table 2
Car Size and Observed Loading in SI Units

Capacity kg (lb)	Car Inside (mm) Wide	Deep	Area (m^2)	Observed Loading[1] (People)
1200 (2640)	2100	1300	2.73	10
1400 (3080)	2100	1450	3.05	12
1600 (3520)	2100	1650	3.47	16
1600 (alt.)	2350	1450	3.41	16
1800 (3960)	2100	1800	3.78	18
1800 (alt.)	2350	1650	3.88	18
2000 (4400)	2350	1800	4.23	20
2250 (4950)	2350	1950	4.58	22
2700 (5940)	2350	2150	5.05	25

[1]See footnote on Table 3.

Table 3
Car Size and Observed Loading in English Units

Capacity (lb)	Car Inside (in) Wide	Deep	Area (ft^2)	Observed Loading[1] (People)
2000	68	51	24.1	8
2500	82	51	29.0	10
3000	82	57	32.5	12
3500	82	66	37.6	16
3500 (alt.)	92	57	36.4	16
4000	82	73	41.6	19
4000 (alt.)	92	66	42.2	19
4500	92	77	46.0	21
5000	92	77	49.2	23
6000	92	90	57.5	27

[1]This loading is given by Strakosch (1983) as that for which passengers will not board an elevator and choose to wait for the next one.

When elevator doors open, the doors remain open for a least fixed time referred to as the dwell-time, t_{dw}. The time that the door is open can be extended beyond the dwell-time by blocking of the light beam across the door opening or by pushing the door safety edge. The time, t_i, for N people to enter an elevator car can be expressed as

$$t_i \begin{cases} t_{dw} & \text{for } N \le 2 \\ t_{dw} + t_{io}(N - N_{dw}) & \text{for } N > 2 \end{cases} \tag{5}$$

where the N_{dw} is the number of people entering the elevator during the dwell time, and t_{io} is the average time for one person to enter the elevator. The number of people entering the elevator during the dwell time is the term (t_{dw}/t_{io}) rounded down to the nearest integer. The time for N people to leave an elevator can be expressed in a similar manner.

$$t_u \begin{cases} t_{dw} & \text{for } N \le 2 \\ t_{dw} + t_{uo}(N - N_{dw}) & \text{for } N > 2 \end{cases} \tag{6}$$

For the computer program of this paper, the dwell-time is taken to be 4 seconds, the average time for one passenger to enter an elevator is taken to be 1 second, and the average time for one passenger to leave an elevator is taken to be 0.6 seconds.

Travel Time

Elevator motion is depicted in Figure 4 for most trips. Motion starts with constant acceleration, followed by transitional acceleration, and constant velocity motion. Constant acceleration ends when the elevator reaches a predetermined velocity which is typically about 60% of the normal operating velocity ($V_1 = 0.6V_m$). For office buildings, the normal operating velocity is generally from 1 to 9 m/s (200 to 1800 fpm), and acceleration is from 0.6 to 2.4 m/s^2 (2 to 8 ft/s^2). Deceleration has the same magnitude as the acceleration, and the total acceleration time equals the total deceleration time ($t_2 = t_5 - t_3$). The method of analysis that follows takes advantage of this symmetry.

Analysis of elevator motion that reaches the normal operating velocity is presented next. For short trips elevators do not always reach the normal operating velocity, and methods of analysis for these short trips are presented later.

Motion Reaching Normal Operating Velocity

The time to complete constant acceleration motion (going to point 1 on Figure 4) is

$$t_1 = \frac{V_1}{a} \tag{7}$$

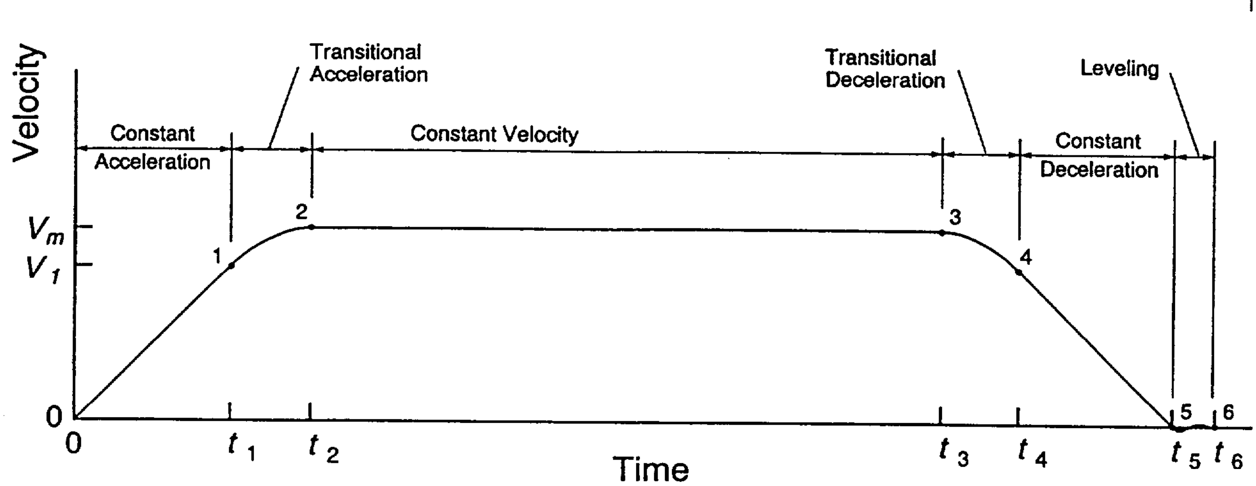


Figure 4. Velocity of elevator reaching normal operating velocity, V_m

The distance traveled during constant acceleration is

$$S_1 = \frac{V_1^2}{2a} \tag{8}$$

Transitional acceleration is approximated by considering the product of velocity and acceleration to be a constant. The time to reach the end of transitional acceleration (point 2 of Figure 4) is

$$t_2 = \frac{V_m^2 - V_1^2}{2V_1 a} + t_1 \tag{9}$$

Then considering the product of velocity and acceleration as constant is an idealization that results in a motion curve that is not smooth near point 2 on Figure 4. At point 2 there is a discontinuity of acceleration resulting in jerk (time rate of change of acceleration). The presence of jerk tends to damage elevator machinery, thus elevator manufacturers avoid jerk in practice. However, more accurate equations of transitional acceleration are not available. Transitional acceleration is a small part of elevator motion, so the errors of Equation 9 result in small errors in travel time. Uncertainties associated with people loading and unloading and other people movement are much larger than the uncertainties associated with elevator motion. Thus for the application of this paper, the approximate nature of Equation 9 is not a concern.

The distance traveled by the end of transitional acceleration is

$$S_2 = \frac{1}{3a}\left(\frac{V_m^3}{V_1} - V_1^2\right) + S_1 \tag{10}$$

The one way travel time is

$$t_5 = 2t_2 + \frac{S_T - 2S_2}{V_m} \tag{11}$$

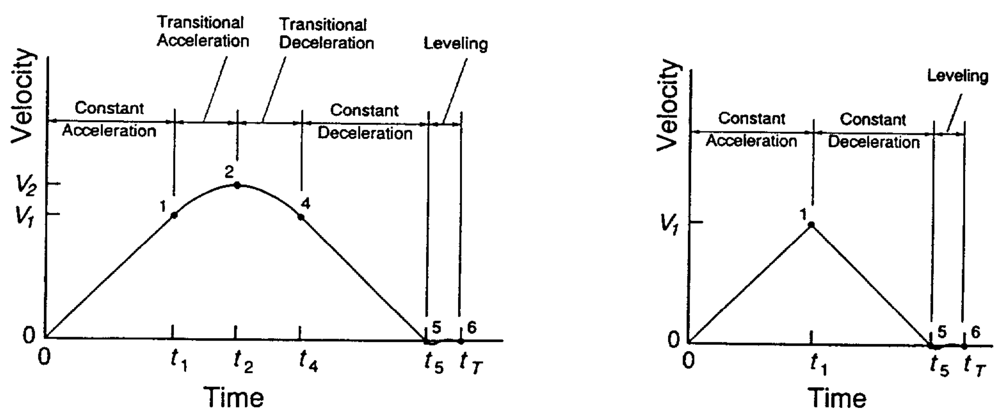
The leveling time must be added to the above time to get the total travel time for a one way trip.

$$t_T = t_5 + t_h \tag{12}$$

Usually elevators do not stop exactly at the desired floor at the end deceleration, so the elevator must be moved slowly up or down to get it nearly level with the floor. For calculations in this paper, leveling time, t_h, is taken to be 0.5 seconds.

Motion Reaching Transitional Acceleration

If the trip is too short for the elevator to reach the normal operating velocity, but it reaches transitional acceleration, the velocity is represented by Figure 5. The time, t_1, and distance, S_1, traveled during constant acceleration are given by Equations 7 and 8.



(a) Car Reaching Transitional Acceleration

(b) Car Not Reaching Transitional Acceleration

Figure 5. Velocity of elevators not reaching normal operating velocity

The velocity at the end of transitional acceleration is

$$V_2 = \left[V_1^3 + 3aV_1\left(\frac{S_T}{2} - S_1\right)\right]^{1/3} \tag{13}$$

The previous comments about the approximate nature of Equation 9 also apply to Equation 13. The time at the end of transitional acceleration is

$$t_2 = \frac{V_2^2 - V_1^2}{2aV_1} + t_1 \tag{14}$$

The one way travel time is

$$t_T = 2t_2 + t_h \tag{15}$$

Motion Not Reaching Transitional Acceleration

When the trip does not go beyond constant acceleration, the motion can be thought of as that illustrated in Figure 5b. The motion illustrated in Figure 5b results in jerk and would be avoided in practice. As with transitional acceleration, the approximate nature of this motion is not be a concern for the application of this paper. The one way travel time is

$$t_T = 2\sqrt{\frac{S_T}{a}} + t_h \tag{16}$$

Example of Evacuation Time Calculated by ELVAC

In this example, the time needed for elevator evacuation of all the people from the upper 11 floors of a 21 story building is estimated. Additionally, 3% of the people on the other floors are included in the elevator evacuation. The rest of the people on the lower floors will use the stairs. Each floor is occupied by 90 people. A group of six 1600 kg (3500 lb) elevators are used for the evacuation, and the elevator doors are 1200 mm (48 in) wide, center opening. One of the six cars is considered out-of-service, thus only five of the cars are used in the analysis. Other parameters of this example are listed in Table 4.

ELVAC was developed to be easy to use. The following is a discussion of running ELVAC for this example, where the data for this example is given in **bold** type. However, there are some digressions to explain some of ELVAC's features. If readers want to make an ELVAC run of this example, they should enter data as described in this section. The ELVAC program, written in Quick BASIC, is available from the Building and Fire Research Bulletin Board System (BFRBBS). There is no cost to down load ELVAC from BFRBBS other than the telephone call (301) 921-6302.

First ELVAC asks if the user wants to read about the model (Y or N). If this is a user's first experience with ELVAC, the user may want to type **Y** so that the computer will list the basic concepts of the model. ELVAC asks for the title of this run, and the user types **Example 21 story elevator group.** The user is asked to select a unit system (1 for SI units and 2 for English units), and **1** was entered for SI units. The user then is asked to enter the floors that the elevators serve, and **1-21** specifies floors 1 through 21.

Table 4
Parameters for Example Calculations

# of Stories	21
# of Elevator Cars	5
# of People/Floor	90
% of People Evacuating by Elevators from Floors 2-10	3
% of People Evacuating by Elevators from Floors 11-21	100
Height between Floors	3.2 m
Operating Velocity of Car, V_m	3.0 m/s (590 fpm)
Car Acceleration, a	1.20 m/s^2 (3.94 ft/s^2)
Other Transfer Inefficiency, γ	0
Trip Inefficiency, η	0.10
Car Full Load	16 people

If the building of this example had no 13th floor, the user would have entered 1-12 14-21. If the user had wanted to specify elevators that serve the basement (B), ground floor (G), and floors 1 through 6; the user would have entered B G 1-6.

The user is asked for the typical floor to floor height, and **3.2** m was entered. The user is asked to enter any exceptions to the typical value. In this example, there are no exceptions so the user enters **end** to stop the exceptions. The user could have specified any number of exceptions. This same approach is used later to specify the number of people on each floor and the percent of people on a floor that use the elevator. This approach takes advantage of the repetitive nature of most buildings, but allows deviations from the typical on any number of floors.

In the same interactive manner the program asks for the discharge floor (**1**), the time to the outside after leaving the elevator (**30** s), the trip inefficiency factor (**0.1**), the number of elevator cars in the group (**5**), the normal operating velocity (**3** m/s), the car acceleration (**1.2** m/s^2), and the elevator full load (**16** people).

ELVAC prints out a menu of elevator door types (Table 1), and the user selects **H** for center-opening 1200 mm (48 in) wide. If the door type desired was not on the menu, users have the option of specifying their own type. The program asks for the other transfer inefficiency (**0**). The computer then calculates that the startup time for automatically operated elevators would be 41.3 s for this example. The computer asks if the user wants another startup time (Y or N): **N**. ELVAC asks for the typical number of people per floor (**90**). The computer asked for exceptions, and as before **end** was entered to stop the exceptions. ELVAC asks for the percent of people on a typical floor that will be using elevators, and **100**is entered to specify 100% usage is typical. The computer asks for a percent usage exception - floor range, percent, and **2-10 3** indicates that on floors 1 through 10 only 3% of the people use the elevators. The computer asks again for a percent usage exception, and **end** is entered to stop the exceptions. The computer prints a summary of the input data, followed by the calculated evacuation times which are listed in Table 5. ELVAC asks if the user wants to save the output to the printer or to a file. The user has the option to run the program again with different percent usages.

From Table 5 the evacuation time using five elevators is calculated at 1258 s or about 21 minutes. The round trip time for floor 21 is 89.1 s. In order to move 90 people from floor 21, the elevator trips are considered to consist of five trips with a full car (16 people) plus one trip of a partially filled (10 people) car. The time for the partially filled round trip is 78.6 s (not shown in Table 5). Thus the total trip time to move 90 people from floor 21 is 5(89.1) + 78.6 = 524.1 s. This time is listed under the heading "Time per Floor" for floor 21 in the table.

On floor 10 of this example, 3% of 90 people are evacuated by elevator. This is rounded up to three people evacuated by elevator. Because this is done by one trip, the round trip time of 45.8 s listed in Table 5 is for moving 3 people rather than the full car load of 16. The total round trip time of 5395.6 s is sum of all the round trips to move people from all the floors. The evacuation time of about 1260 s (21 min) using 5 elevators was calculated from Equation 1.

Conclusions

1. The ELVAC program can be used to approximate the time needed for a number of people to evacuate using a group of elevators. (For a building with more than one group of elevators, the ELVAC program will need to be used to calculate the evacuation time for each group individually.)

2. The analysis of the elevator motion equations show that they have unrealistic components, i.e., jerk (time rate of change of acceleration) would result from such

Table 5
Elevator Trip and Evacuation Time Calculated by ELVAC Computer Program

Floor	Elevation (m)	(ft)	One Way (s)	RT (s)	People on Floor	% Elevator Evacuation	Round Trips (#)	Sec/ Floor
21	64.0	210.0	24.4	89.1	90	100	6	524.1
20	60.8	199.5	23.4	87.0	90	100	6	511.3
19	57.6	189.0	22.3	84.8	90	100	6	498.5
18	54.4	178.5	21.2	82.7	90	100	6	485.7
17	51.2	168.0	20.2	80.6	90	100	6	472.9
16	48.0	157.5	19.1	78.4	90	100	6	460.1
15	44.8	147.0	10.2	76.3	90	100	6	447.3
14	41.6	136.5	17.0	74.2	90	100	6	434.5
13	38.4	126.0	15.9	72.0	90	100	6	421.7
12	35.2	115.5	14.2	69.9	90	100	6	408.9
11	32.0	105.0	13.8	67.8	90	100	6	396.1
10	28.8	94.5	12.7	45.8	90	3	1	45.8
9	25.6	84.0	11.6	43.7	90	3	1	43.7
8	22.4	73.5	10.6	41.6	90	3	1	41.6
7	19.2	63.0	9.5	39.4	90	3	1	39.4
6	16.0	52.5	8.4	37.3	90	3	1	37.3
5	12.8	42.0	7.4	35.2	90	3	1	35.2
4	9.6	31.5	6.3	33.0	90	3	1	33.0
3	6.4	21.0	5.2	30.8	90	3	1	30.8
2	3.2	10.5	3.8	28.0	90	3	1	28.0
1	0.0	0.0						

Total (RT) round trip time = 5395.6
Start up time = 41.3
Time to get outside after leaving the elevator = 30.0
Evacuation time using 5 elevators = 1258.3

equations. In practice manufacturers avoid this motion to protect elevator machinery.

3. The errors due to this unrealistic motion are not significant for the applications of this paper. This is because of the small contribution of this component to the total evacuation time and the extent of the other uncertainties of elevator evacuation.

ACKNOWLEDGEMENTS

The authors acknowledge the support and encouragement of David Frable of the General Services Administration concerning many aspects of the elevator evacuation research. Harold Nelson of NIST (now of Hughes Associates) provided valuable advice about fire evacuation analysis. Jake Pauls of Hughes Associates also provided valuable advice and comments. Special thanks are due to George Strakosch of Elevator World Incorporated, for his advice and guidance concerning almost every aspect of elevator engineering.

NOMENCLATURE

a acceleration, m/s^2 (ft/s^2)
J number of elevators
m number of round trips
N number of people entering or leaving the elevator
N_{dw} number of people entering or leaving the elevator during the dwell time
S distance, m (ft)
S_T total floor to floor travel distance for trip, m (ft)
t time, s (s)
t_a elevator evacuation start up time, s (s)
t_d time for elevator doors to open and close, s (s)
t_{dw} dwell time for elevator doors, s (s)
t_e evacuation time, s (s)
t_h time for leveling elevator of elevator car, s (s)
t_i time for N people to enter elevator car, s (s)
t_{io} time for one person to enter elevator car, s (s)
t_o travel time from elevator lobby to outside or to other safe location, s (s)
t_r time for elevator car to make a round trip, s (s)
t_s standing time, s (s)
t_u time for N people to leave elevator car, s (s)
t_{uo} time for one person to leave elevator car, s (s)
V velocity, m/s (ft/s)
V_m normal operating velocity, m/s (ft/s)
α basic transfer inefficiency
μ total transfer inefficiency, $\mu = \alpha + \varepsilon + \gamma$
ε door transfer inefficiency
γ other transfer inefficiency
η trip inefficiency

SUBSCRIPTS

T end of leveling car motion (also end of travel)
1 end of constant acceleration motion
2 end of transitional acceleration motion
3 end of constant velocity motion
4 end of transitional deceleration motion
5 end of constant deceleration motion

REFERENCES

1. Sumka, E.H., "Presently, Elevators Are Not Safe in Fire Emergencies," *ASHRAE Transactions*, Vol. **93**, Part 2, pp. 2229-2234, 1987.

2. Bazjanac, V., "Another Way Out?" *Progressive Architecture*, April, 1974, pp. 88-89.

3. Bazjanac, V., *Simulation of Elevator Performance in High-Rise Buildings Under Conditions of Emergency, Human Response to Tall Buildings*, Ed. by D.J. Conway. Dowden, Hutchinson & Ross, Stroudsburg, PA, 1977, pp. 316-328.

4. Pauls, J., *Management and Movement of Building Occupants in Emergencies*, DBR Paper No. 788, National Research Council, Ottawa, Canada, 1977.

5. Pauls, J., Gatfield A.J., and Juillet, E., "Elevator Use for Egress: The Human-Factors Problems and Prospects," *ASME Symposium on Fire and Elevators*, Baltimore, MD, February 19-20, 1991, American Society of Mechanical Engineers, New York, NY, pp. 63-75, 1991.

6. Gatfield, A.J. "Elevators and Fire: Designing for Safety," *ASME Symposium on Fire and Elevators*, Baltimore, MD, February 19-20, 1991, American Society of Mechanical Engineers, New York, NY, pp. 95-107, 1991.

7. Degenkolb, J. "Elevator Usage During a Building Fire," *ASME Symposium on Fire and Elevators*, Baltimore, MD, February 19-20, 1991, American Society of Mechanical Engineers, New York, NY, pp. 76-79.

8. Fox C.C., "Handicapped Use of Elevators," *ASME Symposium on Fire and Elevators*, Baltimore, MD, February 19-20, 1991, American Society of Mechanical Engineers, New York, NY, pp. 80-82.

9. Klote, J.H., Alvord, D.M., Levin, B.M., and Groner, N.E. *Feasibility and Design Considerations of Emergency Evacuation by Elevators*, National Institute of Standards and Technology, NISTIR 4870, 1992.

10. Klote, J.H., Deal, S.P., Levin, B.M., Groner, N.E., and Donoghue, E.A. *Workshop on Elevator Use During Fires*, National Institute of Standards and Technology, NISTIR 4993, 1992.

11. Groner, N.E. and Levin, M.L., *Human Factors Considerations in the Potential for Using Elevators in Building Emergency Evacuation Plans*, National Institute of Standards and Technology, NIST-GCR-92-615, 1992.

12. Klote, J.H. and Alvord, D.M. *Routine for Analysis of the People Movement Time for Elevator Evacuation*, National Institute of Standards and Technology, NISTIR 4730, 1992.

13. Nelson, H.E. and MacLennan, H.A., "Emergency Movement," *SFPE Handbook of Fire Protection Engineering*, Society of Fire Protection Engineers, 1988.

14. Pauls, J., "People Movement," *SFPE Handbook of Fire Protection Engineering*, Society of Fire Protection Engineers, 1988.

15. ASME 1987. *American Standard Safety Code for Elevators, Escalators, Dumbwaiters and Moving Walks*, A17.1, American Society of Mechanical Engineers, New York.

16. Strakosch, G.R., *Vertical Transportation: Elevators and Escalators*, 2nd Edition, Wiley & Sons, New York, NY, 1983.

PROCEEDINGS

PERFORMANCE-BASED FIRE SAFETY ENGINEERING

15-17 NOVEMBER 1993

Performance-Based Codes: The New Zealand Experience (Richard J. Fraser)

A Firesafety Performance Study Using NRCC Risk-Cost Assessment Model
(Dr. George Hadjisophocleous, P.Eng., & Dr. David Yung, P.Eng.)

Selection and Specification of the "Design Fire" for Performance-Based Fire Protection Design
(Richard L.P. Custer)

Structural Fire Resistance Analysis of a Diesel Engine Driven Power Generating Plant: A Performance-Based Design Approach (Thomas Capaul & Brian J. Meacham, P.E.)

Developing a Performance-Based Sprinkler System Standard (James M. Feld, P.E.)

The Federal Fire Safety Act of 1992: Impact on Fire Protection Engineering
(Donald G. Bathurst & David W. Stroup, P.E.)

Concrete Hazardous/Radioactive Waste Storage Facilities: Fire Development and Hazard Analysis
(Sean P. Hunt)

Using Performance-Based Analysis to Assess Fire Hazard and Develop Governing Criteria for a Combustible Fuel Package in Facilities (Eric R. Rosenbaum, P.E.)

Design and Analysis of Fire Detection Systems Using a Goal-Oriented Approach (Christopher E. Marrion)

Practical Applications of Quantitative Analytical Tools in Support of Fire Hazard Analyses
(David S. Mowrer, P.E.)

Computer Fire Modeling Analysis of Smoke Control System Performance in an Arena (Warren D. Bonisch, P.E.)